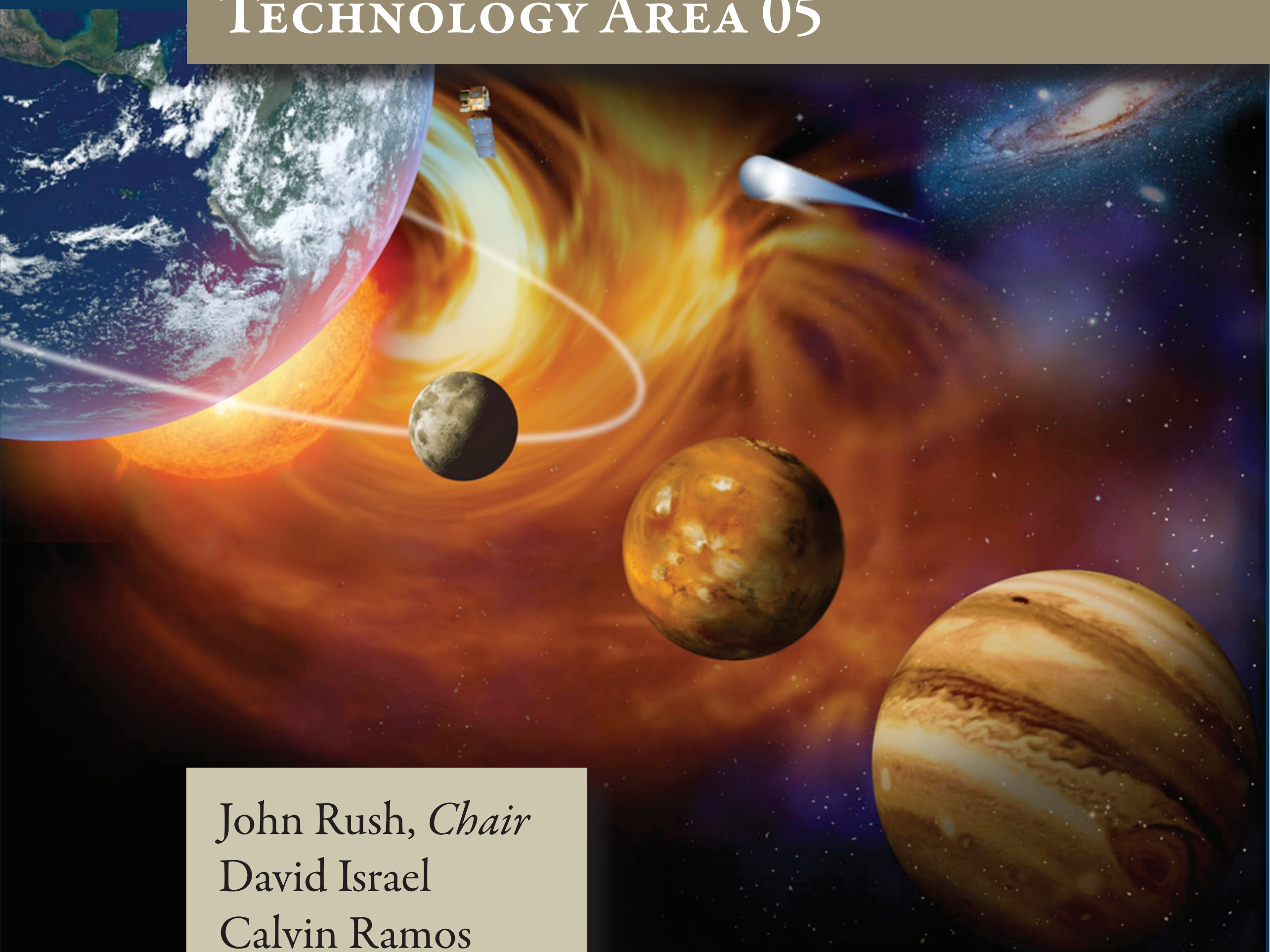
National Aeronautics and Space Administration

DRAFT Communication and Navigation Systems Roadmap

Technology Area 05



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FOREWORD

NASA's integrated technology roadmap, including both technology pull and technology push strategies, considers a wide range of pathways to advance the nation's current capabilities. The present state of this effort is documented in NASA's DRAFT Space Technology Roadmap, an integrated set of fourteen technology area roadmaps, recommending the overall technology investment strategy and prioritization of NASA's space technology activities. This document presents the DRAFT Technology Area 05 input: Communication and Navigation Systems. NASA developed this DRAFT Space Technology Roadmap for use by the National Research Council (NRC) as an initial point of departure. Through an open process of community engagement, the NRC will gather input, integrate it within the Space Technology Roadmap and provide NASA with recommendations on potential future technology investments. Because it is difficult to predict the wide range of future advances possible in these areas, NASA plans updates to its integrated technology roadmap on a regular basis.

EXECUTIVE SUMMARY

The Communication and Navigation Technology Area supports all NASA space missions with the development of new capabilities and services that make our missions possible. Communication links are the lifelines to our spacecraft that provide the command, telemetry, and science data transfers as well as navigation support. Planned missions will require a slight improvement in communication data rates as well as moderate improvements in navigation precision. How-ever, advancement in communication and navigation technology will allow future missions to implement new and more capable science instruments, greatly enhance human missions beyond Earth orbit, and enable entirely new mission concepts. This will lead to more productivity in our science and exploration missions as well as provide high bandwidth communications links that will enable the public to be a part of our programs of exploration and discovery.

Today our communication and navigation capabilities, using Radio Frequency technology, can support our spacecraft to the fringes of the solar system and beyond. Data rate range from 300 Mbps in LEO to about 6 Mbps at Mars. As we move into the future there are a set of challenges that will face the communication and navigation technology area:

- As capabilities of our science instruments advance, new mission concepts are developed, and human exploration intensifies, we must assure that our communication and navigation systems don't become a constraint in planning and executing our missions
- As our missions move farther from Earth our communication and navigation technology must minimize the impacts of latency in planning and executing NASA space missions
- While we advance the capabilities of our communication and navigation systems and improve their performance we must assure that we minimize user mass, power, and volume burden on our missions
- In the future we envision serving a wider and more interactive public which could in-crease security vulnerabilities and therefore must assure that we provide integrity and assurance of information delivery across the solar system
- Communication and navigation services must be realized with reduced lifecycle cost
- In order to validate and infuse new communication and navigation technology we must demonstrate to missions that it performs with acceptable risk—but a lack of demonstration opportunities hinders this process.

In order to address these challenges a communication and navigation technology area roadmap has been developed that includes identification of focus areas. One of the focus areas continues to develop RF technology while initiating a parallel path to develop optical communications capability. As RF technology development concentrates on getting more productivity out of the constrained spectrum bands that are allocated to space users, optical communication seeks to take advantage of the virtually unconstrained bandwidth available in the optical spectrum. In addition, the roadmap includes the migration of the Earth's internetworking technology and processes throughout the solar system. The expansion of internetworking will help lower operational costs of our systems by replacing manual scripting and commanding of individual spacecraft communication links with autonomous handling of data distribution similar to that of the terrestrial internet. The position, navigation and timing focus area addresses the key technology efforts necessary to improve navigation through investments in timing accuracy and distribution as well as make autonomous navigation available for precise maneuvers, such as rendezvous and docking, anywhere in the solar system. Realizing that there may be advantages to integrating technology developed across the communication and navigation area, a focus area is identified in the roadmap that concentrates on this integration. This focus area also includes the integration of communication and navigation technology developed in other technology areas such as in computing technology and advanced sensors. Since there may be game changing technology that could completely change the way we communication and navigate in the future "revolutionary technology" is identified for possible development investments. Much of this focus area is currently at a low TRL concept development stage.

The technology area strategic roadmap (TASR) describes the communications and navigation technology developments that are necessary to meet the needs of future missions, provide enhanced capabilities or enable new mission concepts. Representative future missions are shown at the top. Below this are key capabilities/investments that NASA will need to undertake to enable or enhance these missions. In some cases technology can be directly infused into missions after it has been demonstrated in the laboratory. In other cases, where there is a major technology upgrade and significant risk to the missions, a successful flight demonstration must be conducted and any new infrastructure required must be in place prior to mission use. These two cases are depicted in the roadmap by triangle milestones for direct infusion into missions and by squares for milestones that require flight demonstrations and/or major infrastructure investments prior to mission use. For example, surface wireless needs to be at TRL 6 by 2019 in order to enable development of an autonomous networking capability in the 2027 timeframe, while hybrid optical com and navigation sensing will require flight demonstration in 2021 in order to allow pinpoint landing capability and enable missions not possible today. In this case the demonstration is necessary because of the level of risk to the mission involved in introducing this radically new navigation technology. As can be seen in the TASR, technology development must begin long before its benefits can be realized by the missions. The rows below the key capabilities/investments in the TASR identify the main technology focus areas that form the basis of the Technical Area Breakdown Structure (TABS)

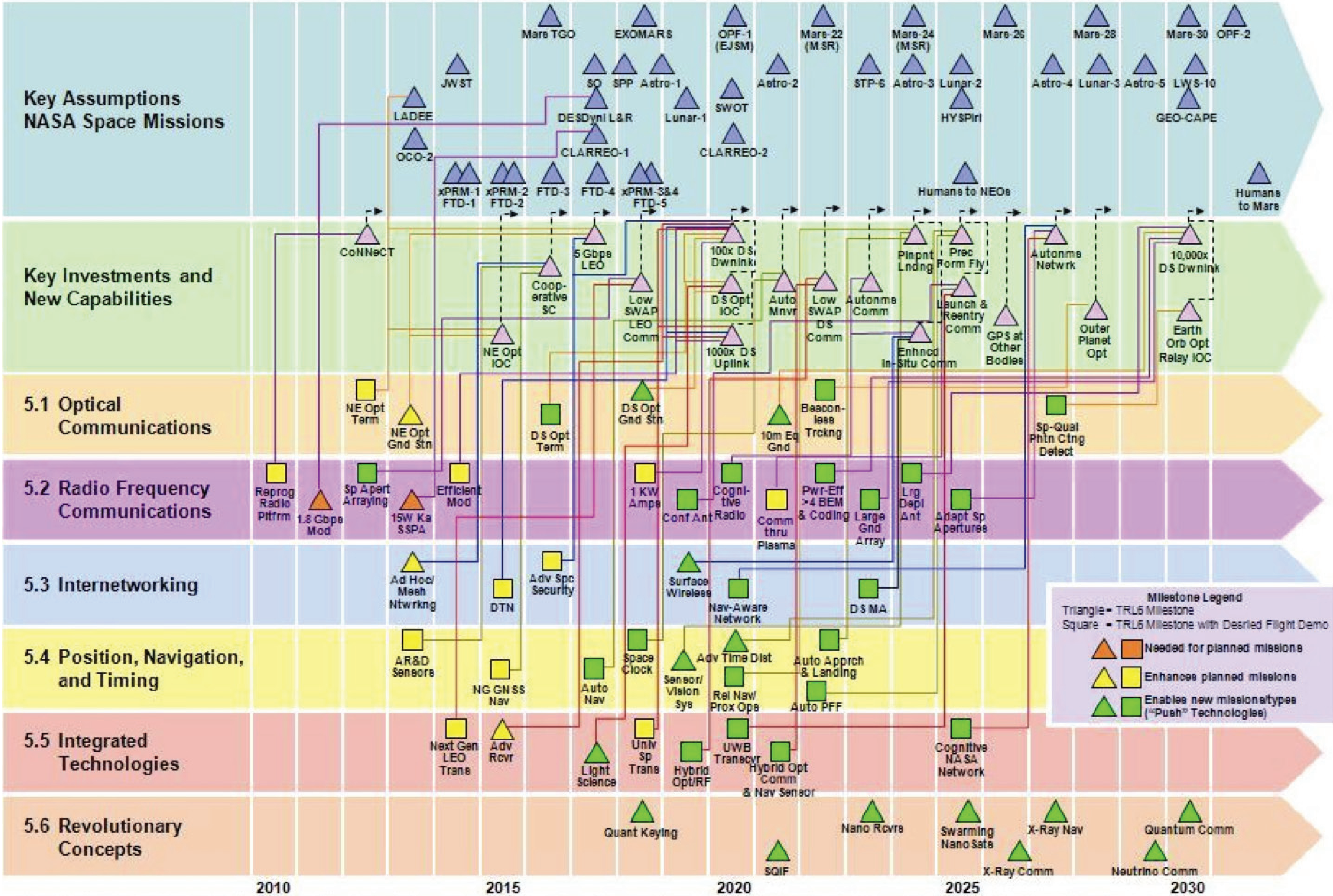
In the TASR, pull technologies, those that enable missions currently within the Agency's plans, are connected directly to the missions that require them, e.g. the CLARREO-1 mission will fly a 15 W Ka-band SSPA. Later missions that are not completely defined as of yet require push technologies to enable their objectives. Push technologies enable new capabilities that enable missions not currently possible. In addition, all missions require some form of both communications and navigation, it is expected that all missions that fly after the development of a key investment/capability will take advantage of it in their definition. Hence "Humans to NEO" would likely use the "100x Deep Space Downlink", "Pinpoint Landing", and "Low SWAP Deep Space Communications". Therefore, these technologies are linked to the key capabilities. Many capabilities will require technology maturity from multiple technology development initiatives. The technology milestones represent achieving TRL 6. Adequate time for each is provided in the TASR for their infusion into the operational communication and operations infrastructure.

As is indicated in the roadmap, there are several communication and navigation technology development efforts that will directly benefit currently planned missions. Of the developments directly applicable to planned missions Low Density Parity Coding (LDPC) and a 15 w Ka-band Solid State Power Amplifier (SSPA) would improve mission performance as would the development of Software Defined Radio (SDR) technology for the next LEO standard S-band transceiver and the Universal Space Transceiver (UST) operating in Ka-band.

However, major communication and navigation capability advancements would result from in-vestments in the technology focus areas in the roadmap, thus enabling new classes of missions; several highlights are included below.

- **Optical Communication:** Development of photon counting detector technology focuses on new materials and attempts to raise the operating temperature for use in spacecraft. Laser power efficiency improvements will help pave the way for higher power lasers needed for communication from deep space. Addressing spacecraft induced jitter will improve laser beam pointing capability. Initially optical terminals on spacecraft will use Earth-based beacons but eventual beacon-less pointing will be developed.
- **RF Communications:** RF communication will develop new techniques that will allow at least two orders of magnitude increase over current data rate capabilities in deep space. Cognitive radios will be developed that will sense their environment, autonomously determine when there is a problem, attempt to fix it, and learn as they operate. Communication through harsh environments such as rocket plumes and re-entry ionization will be addressed with technology such as Ultra Wide Band (UWB) radios.
- **Internetworking:** Earth-based internetworking technologies will be migrated to space with protocols such as Disruptive Tolerant Networking (DTN) which will help deal with latency issues and automate distribution of data where ever our spacecraft operate.
- **Position, Navigation, and Timing:** Fundamental to the improvement of our navigation capability is the improved accuracy and stability of our space clocks so significant focus will be on this area. Algorithms for autonomous rendezvous, docking, landing, and formation flying will be developed.
- **Integrated Technologies:** Development of hybrid optical and RF communication systems should reduce mass and power requirements on

Figure R: *Communication and Navigation Systems Technology Area Strategic Roadmap (TASR)*



(BEM = Bandwidth Efficient Modulation; DS = Deep Space; IOC = Initial Operational Capability; LEO = Low Earth Orbit; MA = Multiple Access; NE = Near Earth; SC = Spacecraft; Sp = Space; SWAP = Size, weight, and power; UWB = Ultra Wide Band)

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spacecraft. Integrating knowledge engineering with future networking radios could provide cognitive networking functionality which would further reduce dependence on manual control from Earth. Techniques will be developed to improve the use of the RF link as a science instrument (measuring perturbations along its path or in the spacecraft trajectory) and enable these kinds of measurements using optical links.

- **Revolutionary Technologies:** Advancement of X-ray navigation using X-ray emitting pulsars could provide the ability to autonomously determine position anywhere in the solar system just as GPS does for Earth inhabitants. Successful development of Superconducting Quantum Interference Filter (SQIF) technology would change the paradigm for RF communication to detecting the magnetic field instead of the electric field and provide magnitudes of improvement in our communication systems.

Many of the technology developments captured in this roadmap are of interest to other US Government agencies and provide opportunities for collaboration. In addition, the development of these technologies will directly benefit commercial sectors such as the telecommunication industry and help promote the competitiveness of the US industrial base.

1. GENERAL OVERVIEW

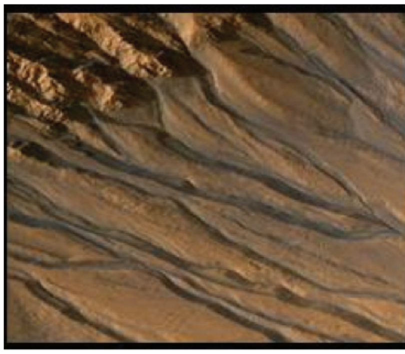
1.1. Technical Area

NASA's space communication infrastructure provides the critical life line for all space missions. It is the means of transferring commands, spacecraft telemetry, mission data, voice for human exploration missions, maintaining accurate timing and providing navigation support. As mission capabilities grow, the capability of the space communication infrastructure must grow faster to avoid constraints on missions and to enable missions never before imagined. The vision of the future will transform the present NASA space communication and navigation capability from one of being a connection provider to being a flexible service provider as we extend internet-worked technologies and techniques throughout the solar system and beyond. This vision includes enabling spacecraft to autonomously navigate and communicate back to Earth over self forming networks that are tolerant of disruptions.

In order to bring about this transformation of our space communication capability, we must make continuing investments in new technology. There is still enormous potential in further development of RF technology that will help provide the higher data rates that will be needed in the future in order to not constrain new mission capabilities. But there is also enormous potential in developing optical communication to a level of availability that matches that of RF communication and unbridles the unrestricted optical bandwidth for order of magnitude advances over present RF capabilities. Position, Navigation and Timing technology advancement will lead to the ability for spacecraft to navigate autonomously anywhere in the solar system. The vision of extending the internet to space will require investments in not only development of new protocols and network topologies but also new ways of providing a secure environment for the vital communications links that will be needed in the future. And the transformation to the future could leap ahead if investments in revolutionary concepts result in new "game changing" capabilities. The communication and navigation roadmap that follows provides the blue print for achieving this vision. The roadmap is aligned with NASA missions as projected at this time and, if followed, will meet emerging mission capability needs as well as provide new opportunities to expand mission capabilities in the future.

1.2. Benefits

Communications and navigation are enabling services that are required by all spacecraft. Investments in communication and navigation technology will ensure that future NASA missions are not constrained by a lack of communication or navigation capability. It will allow our missions to take advantage of more capable science instruments that will evolve in the future. For example, on MRO, data collection for climate observations



This recent image taken by the Mars Reconnaissance Orbiter represents what one could see from a helicopter ride at 1000 feet above the planet. While this mission is collecting some of the highest resolution images of Mars to date and it will collect 10 to 20 times more data than previous Mars missions, bandwidth is still a bottleneck.

Figure 1. *Mars Reconnaissance Orbiter (MRO) Example*

must be turned off while not over the poles because we cannot get the data back. At MRO's maximum data rate of 6 Mbps (the highest of any Mars mission to date), it takes nearly 7.5 hours to empty its on-board recorder and 1.5 hours to transfer a single HiRISE image to Earth. In contrast, it will be possible within the next few years, with appropriate technology development, to have either an RF or an optical communications solution at 100 Mbps such that the recorder onboard a spacecraft at Mars could be emptied in 26 minutes, and an image could be transferred to Earth in less than 5 minutes. And if the solution is optical communications, a few cm-level ranging can drastically improve the spacecraft positioning and thus quality of science data.

Technology investments in PNT will benefit both human spaceflight and robotic spaceflight. More precise positioning will enable higher quality data return from science instruments such as hi-resolution cameras, and will enable mission operations such as precise landing and deep space formation flying that are not possible with today's navigation capability.

Sub-meter positioning will be needed for precision formation flying missions and a pinpoint landing capability on the order of 100-meters will be required to land crews proximate to pre-positioned supplies. In addition, improvements in areas such as the use of GNSS in Earth orbit will enable autonomous navigation which ultimately will reduce the cost of mission operations and enable mission capabilities (e.g., autonomous rendezvous, proximity operations and docking) beyond LEO. The benefits that would accrue to human spaceflight would include reduced mission risk, lowered operations costs through significantly less ground-control intervention, and new capabilities for robotic pre-positioning of key assets and, subsequently, for crewed precision landings on planetary and/or NEO surfaces.

Extending networking to space will decrease the cost of missions through autonomous transfer of data where today such transfers involve high levels of manually scheduling and scripting. This will be analogous to how the terrestrial internet autonomously transfers information without human intervention. However, due to the disruptive nature of the space environment (long latency and intermittent connectivity), new protocols and network architectures will need to be developed.

Development of communication technology will also benefit the average American citizen through improved agency outreach to the public and educational institutions. Improvements in communications will allow extension of the exploration experiences into the home and classrooms of the general public. Data can be disseminated to experimenters in near real-time to allow for improved experiments and provide telescience capability. Live audio and video delivery allow for direct public involvement into the engineering challenges and excitement of scientific discovery.

1.3. Applicability/Traceability to NASA Strategic Goals, AMPM, DRMs, DRAs

The immediate goal of the communication and navigation technology development effort is to address any deficiencies identified by established missions. A secondary, long term goal is to provide NASA with new communication and navigation capabilities that the missions can then use to provide new mission capabilities including enhanced public engagement. These goals are derived from the following policies and requirements discussed below.

1.3.1. National Space Policy

The newly released "National Space Policy" states "Space operations should be conducted in ways that emphasize openness and transparency to improve public awareness of the activities of government, and enable others to share in the benefits provided by the use of space". NASA's communications systems are critical to fulfilling this goal and this technology area will enable this by extending Internet-like connectivity everywhere NASA explores. Furthermore, most of the "goals" are directly enabled by a strong NASA communications and navigation capability. In addition, these same systems will enable the sharing of emergency information as outlined in the Policy.

1.3.2. Agency Mission Planning Manifest (AMPM)

Each specific mission in the AMPM and each likely mission concept to be proposed for future competitions is analyzed to understand the likely communications and navigation desires. These are turned into trends in major figures of merit (FOMs). All technology investments in this area are tied to these trends or to their extrapolation—the latter creating push technologies.

1.3.3. NASA Communications and Navigation Infrastructure Requirements

These NASA requirements shape the Agency's current communication and navigation technology investments and can serve a guide for future investments in this area. The current requirements include:

a. Develop a unified space communications and navigation network infrastructure capable of meeting both robotic and human exploration mission needs

b. Implement a networked communication and navigation infrastructure across space

c. Provide the highest data rates feasible for both robotic and human exploration missions

d. Assure data communication protocols for Space Exploration missions are internationally interoperable

Since there is a requirement for international interoperability, select technology development tasks in the internetworking and RF technology areas will be conducted in coordination with the international standards bodies such as the Consultative Committee for Space Data Standards (CCSDS).

1.4. Top Technical Challenges

1.4.1. Avoid communication from becoming a constraint in planning and executing NASA space missions

A recent analysis of NASA's likely future mission set indicates that communications performance will need to grow by about a factor of ten every ~15 years just to keep up with what we believe will be robotic mission requirements. A second dimension of the challenge is measured simply in bits per second. History has shown that NASA missions tend to return more data with time according to an exponential "Moore's Law".

Missions will continue to be constrained by the legally internationally allocated spectral bandwidth. NASA's S-band is already overcrowded and there are encroachments at other bands.

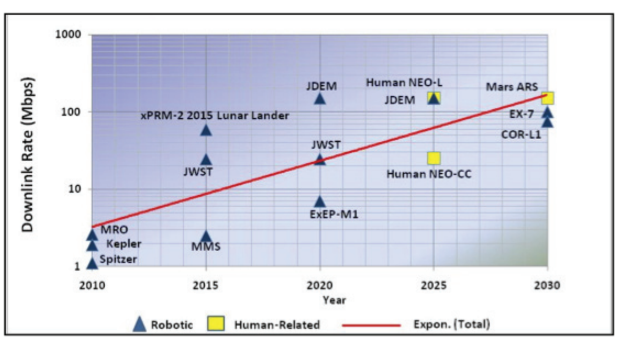


Figure 2. *Downlink Rate Drivers as a Function of Time*

1.4.2. Avoid navigation from becoming a constraint in planning and executing NASA space missions

NASA's future missions show a diverse set of navigational challenges that we cannot currently support. Precision position knowledge, trajectory determination, cooperative flight, trajectory traverse and rendezvous with small bodies are just some of the challenges that populate these concepts. In addition, our spacecraft will need to do these things farther from Earth and more autonomously than ever before. Proper technology investment can solve these challenges and even suggest new mission concepts.

1.4.3. Minimize the impacts of latency in planning and executing NASA space missions

Many of the complex things future missions will need to do are hampered by keeping Earth in the real-time decision loop. Often, a direct link to the Earth may even not be available when such decisions are desired. This can be mitigated by making decisions closer to the platform – minimizing reliance on Earth operations. To do this, the communications and navigation infrastructure must be advanced to allow information to be gathered locally and computation to be per-formed either in the spacecraft or shared with nearby nodes. Space Internetworking is an example of an enabling technology in this area. Clearly this goal is coupled with the need for in-creased autonomy and flight computing. Technology investment can solve these challenges and even suggest new mission concepts.

1.4.4. Minimize user mass, power, and volume burden while improving performance

Future missions will demand increased communications and navigation performance. This performance must be delivered while reducing mass, power, and volume burden on the spacecraft. This can be measured by metrics such as Watts per data bit or kg per data bit. This will allow more resources for crew or science instruments.

1.4.5. Provide integrity and assurance of information delivery across the solar system

Future missions will have increased international partnerships and increased public interaction. This will imply increased vulnerability to information compromise. As mentioned in the 2012 Science and Technology Priorities Memo from the

Table 1. *Example Challenge Progress Goals*

Challenge	Example Progress Goals		
	Near-term (thru 2016)	Midterm (2017-2022)	Far-term (2023-2028)
1 Remove Comm. as a Constraint		200 Mbps from 1 AU 30 Gbps from LEO	20 Gbps from 1 AU 3 Tbps from LEO
2 Remove Nav. as a Constraint	Increased reliance on next generation international GNSS (GPS, GLONAS, Galileo) receiver based navigation below GEO as well as a technology push for in-situ navigational observations, sensor data fusion, and autonomous PNT	Increased reliance on in-situ observations, data fusion, and autonomous PNT; supervised autonomy for missions beyond GEO	Fully autonomous PNT functions for all missions throughout the solar system; GPS-like navigation at Mars
3 Minimize Impact of Latency	Navigation/timekeeping to support -Semi-Autonomous pinpoint landing with 100-m accuracy: - Millimeter-level formation control	Navigation/timekeeping to support: -Autonomous pinpoint landing with 10-m ac-curacy - Micrometer-level formation control	Navigation/timekeeping to support: -Autonomous pinpoint landing with 1-m accuracy - Nanometer-level formation control
4 Minimize user burden		Reduction of 50% in transponder mass	Reduction of 75% in transponder mass
5 Integrity & Assurance	Interplanetary info security including international trust relation-ships with conditional security levels Validate unconditional information security techniques to low-Earth orbit (LEO)	Standard international trust relationships established and managed operationally Unconditional information security techniques employed with LEO and some deep-space missions	Global information trust relationships Internationally-standard unconditional information security with all space missions
6 Lower Lifecycle Cost	20% Reduction from current	40% Reduction from current	80% Reduction from current
7 Lack of Demo's	Optical comm. demo	Multi-function SDR demo	Deep space relay tech demo

White House, we need to "Support cybersecurity R&D to investigate novel means for designing and developing trustworthy cyberspace—a system of defensible subsystems that operate safely in an environment that is presumed to be compromised" As we extend Internetworking throughout the Solar System, we need to proceed in a safe and secure manner.

1.4.6. Lower lifecycle cost of communications and navigation services

Future missions will be ever more complex. The current NASA methods of providing communications and navigation services will not scale in a cost-effective way. NASA should work to reduce the cost of providing these services, reducing burden on its operators, even as the mission set expands and becomes more challenging or more cost constrained.

1.4.7. Advancement of Communication and Navigation Technologies Beyond TRL-6

As part of the technology advancement process, in order to advance beyond TRL-6, communication and navigation technologies must be demonstrated in the space environment. However, flight projects are reluctant to assume the risk of carrying demonstration hardware or software, since they must also carry redundant operational systems to ensure mission success. Without demonstrations, flight projects are unlikely to rely on new technology for operational systems. For NASA to realize the benefits of the technology described in this roadmap, flight demonstrations of new technologies must be performed.

2. DETAILED PORTFOLIO DISCUSSION

2.1. Summary description and Technology Area Breakdown Structure (TABS)

The chart below shows the Technology Area Breakdown Structure (TABS) for Communications and Navigation Systems. The technology is divided into six major areas. The first five are viewed as enabling evolutionary developments and the final one is revolutionary.

Optical Communications (5.1) deals with the various technologies required to make communication with light practical.

Radio Frequency Communications (5.2) strives to dramatically accelerate techniques in use today for NASA's missions. Though quite a bit more mature than optical communications, there is still a great deal of promise for technology breakthroughs in the RF domain. However, all RF technology development will be focused on RF spectrum that had been allocated for space use by the International Telecommunication Union (ITU) and where adequate bandwidth would pro-vide a useful service, or where the application is beyond the near Earth environment. Many of the key technical challenges could be met by either optical or RF communications so NASA will invest in both paths, with appropriate decision points. Internetworking (5.3) deals with extending terrestrial Internet-like concepts throughout space.

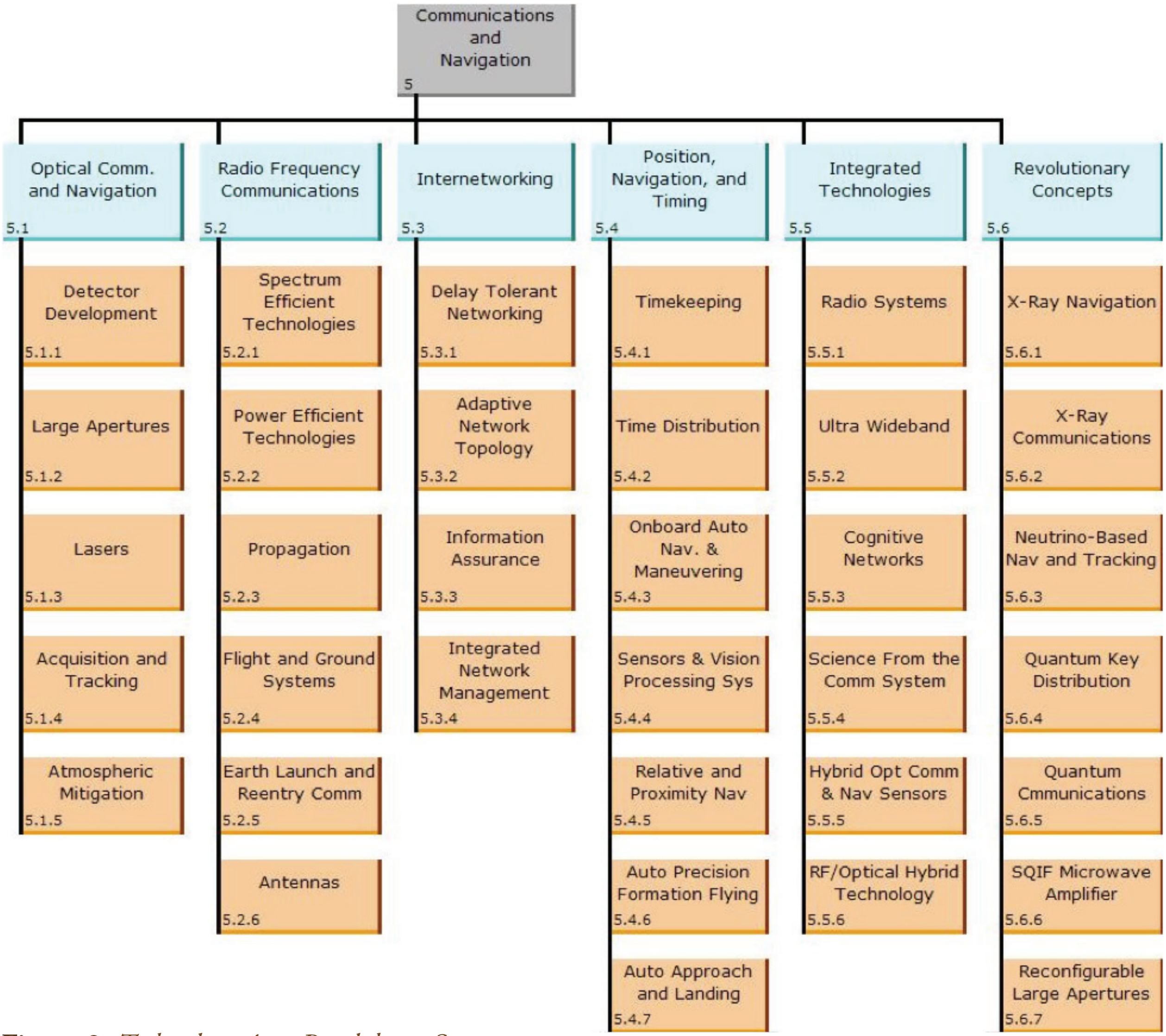


Figure 3. *Technology Area Breakdown Structure*

Position, Navigation, and Timing (5.4) provides all the technologies required to know where our spacecraft and their targets are, understand their trajectories, and synchronize all systems. Integrated Technologies (5.5) deals with crosscutting technologies that work in combination with the other areas to maximize the efficiency of our missions.

Revolutionary Concepts (5.6) are those technology ideas that are truly on the cutting edge. Items placed here are so "far out" that the development approaches are not yet well understood. These are typically items that are simultaneously very high risk but very high payoff if they materialize. As items here mature, they might be moved to other appropriate areas of the Roadmap.

2.1.1. Optical Communications and Navigation Technology

Current Status:

Currently NASA is in the process of migrating its high rate mission data to Ka-band as part of a continuing trend in the demand for high data returns from our science missions. However, it is expected that the trend toward higher data rate needs will continue in the future and will eventually surpass the capacity available with Radio Frequency (RF) Ka-band. At that point in time NASA plans to migrate from Ka-band to optical communication which provides access to unregulated spectrum and will support the data rates that will be needed by the next generation of science instruments. This migration will be especially valuable to our deep space missions, which will be able to realize higher data rates than with RF

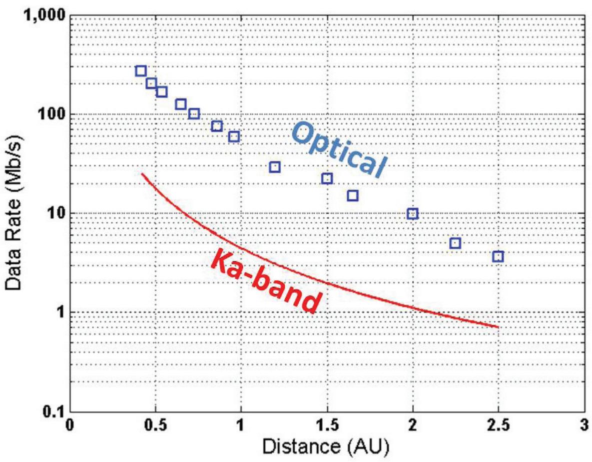


Figure 4. *Ka-band vs. Optical Data Rates*

communications with flight terminals that will impose an equal, or lower, power and mass burden on spacecraft and have significantly less aperture size than RF antennas. The first experimental optical terminals, developed by foreign space agencies, are currently providing high-rate communications demonstrations (up to 6 Gbps crosslink) in low Earth orbit. A common feature of these systems is the use of Earth-based beacons for acquisition and tracking. Longer term, reliance on beacons should be eliminated. It should also be noted that optical communication also has the side benefit of cm-level ranging, an order of magnitude better than RF.

NASA has begun development of optical communication technology with strategic investments in key areas and has progressed to the point where this new capability will be demonstrated on the LADEE spacecraft in 2013. The main goal of this demonstration is to prove the fundamental concepts and transfer up to 622 Mbps from Lunar distance, roughly six times the rate of the Ka-band

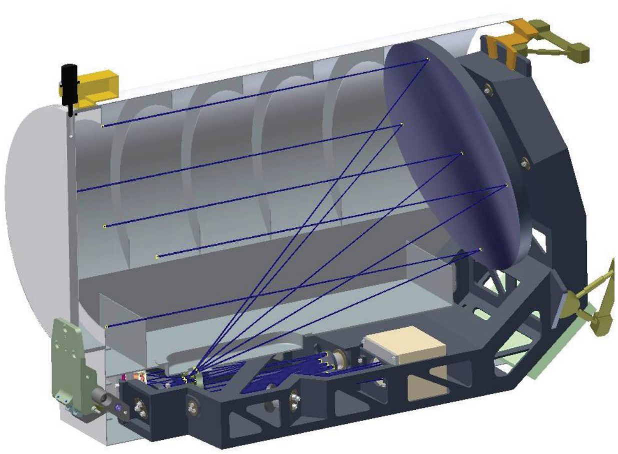


Figure 5. *Deep Space Optical Terminal Concept*

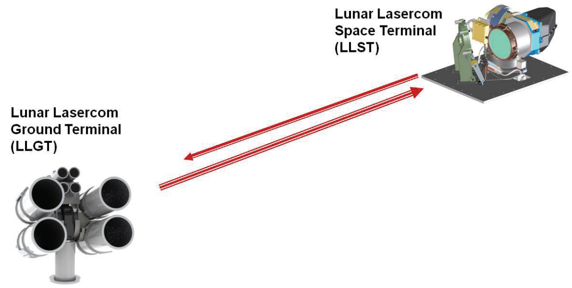


Figure 6. *LADEE Optical Communication System*

system on LRO. The system will also demonstrate Pulse Position Modulation (PPM) which will be a key factor in optical communications from deep space locations in the future. The optical terminal on LADEE will be suited for demonstrating the capability in Near Earth missions. The flight terminal's optical module technology is applicable for use in LEO and GEO applications. However, with the shorter distance coherent modulation should be developed and would replace the PPM system to be used on LADEE. With coherent modulation, this system will be able to operate at the multi-Gbps level at GEO and below. An initial design for a Deep Space Optical Communications Terminal (DOT) is targeted for a potential Mars demonstration mission, transferring 250 Mbps from closest Mars approach. Both systems use supercooled nano-wire technology to provide the best performing ground photon counting detectors. Both the LADEE and DOT optical communication systems will also be able to make very significant improvements in spacecraft position determination with ranging accuracies at the few cm-level.

Major Challenges:

Low received photon density is a major concern, especially for deep space applications where even a laser signal is subject to the classic inverse distance square loss. Extraneous "noise photons" such as might occur when pointing close to the Sun, drive the need to distinguish the transmitted photons. The narrow beam widths involved require precise acquisition and tracking as well as vibration mitigation. Increasing laser lifetime is critical for long-duration missions. At the same time increasing laser power efficiency from the current 10 – 15% to around 30% while decreasing mass and cost will be an important factor in moving optical communication capability forward, especially for deep space applications. Atmospheric conditions including clouds, clear air moisture content, and atmospheric turbulence can be a major challenge to eventual operational acceptance of optical com-

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Table 2. *Mapping of optical communications tasks into the Top Technical Challenges*

	1 Remove Comm. as a Constraint	2 Remove Nav. as a Constraint	3 Minimize Impact of Latency	4 Minimize user burden	5 Integrity & Assurance	6 Lower Life-cycle Cost
Detector Development	X	X		X		X
Large Apertures	X					
Laser Improvements	X	X		X		X
Acquisition and Tracking	X	X				
Atmospheric Mitigation	X			X	X	X

munication. High-performing space-based optical receiver systems will be required for space-based uplinks and relay applications, however, the best performing detectors today require super-cooling.

Overcoming the Challenges:

As depicted in the TASR, the optical communications technology development effort begins with developing the technologies to support near Earth optical communications. This technology progresses from near Earth capabilities to development of larger terminals to support deep space optical communications. Later in the optical communication development process, beaconless tracking will be developed that will enable optical communications for the outer planets. Also, in order to enhance deep space optical communications, technology will be developed to enable Earth-based satellites to relay deep space optical communications to Earth. In order to overcome the challenges listed above, some key initiatives have been identified. Each may address multiple challenges.

Detector Development: Work must continue to improve photon-counting detectors. This includes improving the yield in the assembly of super-cooled nano-wire detector arrays and experimenting with detector performance at higher temperatures. Raising the temperature will allow quicker transition to space-based optical communication receivers such as optical communications relays and mission uplinks. In addition, alternate technology should be investigated such as the Silicon Nano-wire technology, which if successfully developed would be able to operate at higher temperature ranges and be more suitable for space-based use. For applications at GEO and below, coherent modulation/demodulation systems should be developed. This work should be closely coordinated with work outside of NASA where there are common technology development interests.

Large apertures: Development of virtual large apertures for ground reception that cope with the weak received signals will be needed for deep space applications. In addition, light weight space-based large aperture optics or space-based optical arrays that could be obtained at a reasonable cost will open opportunities in terms of higher uplink rates to spacecraft, or development of Earth-based relays for downlinks from spacecraft operating in deep space.

Laser Improvements: Investments in improving space-based lasers should include improvements in amplifiers that enable higher power operations and also focus on extending the lifetime of the terminal. The near term effort should include improvements in pump diode lifetime and increasing laser power to 5 W and above for high data rate deep space applications as well as work to-ward more power efficient lasers.

Acquisition and Tracking: A number of initiatives are needed in order to improve acquisition and tracking of the optical signal. This includes: better vibration mitigation through either passive or active means; improved stabilization systems such as introducing fiber optic gyro (FOG) technology which could effectively extend beacon-aided acquisition beyond Mars; eventual development of beaconless pointing capability which would allow the use of optical communications technology throughout the solar system.

Atmospheric modeling and mitigation: This includes experimenting with reception of signals from spacecraft terminals in varying atmospheric conditions and development of methods for handling the handover of the signal from space to alternate ground stations in the event that clouds or other atmospheric conditions cause disruption of a link. In addition, development of adaptive optics and/or large detector arrays for mitigation of atmospheric turbulence effects on optical signals is needed. In order to accelerate this work, models of optical communication signal performance in the Earth's atmosphere will be developed and validated through experimentation. Subsequent model development will extend the modeling capability to atmospheres of other bodies in the solar system.

Overlaps and Potential Synergies:

To this point all NASA investments in optical communications have been coordinated through

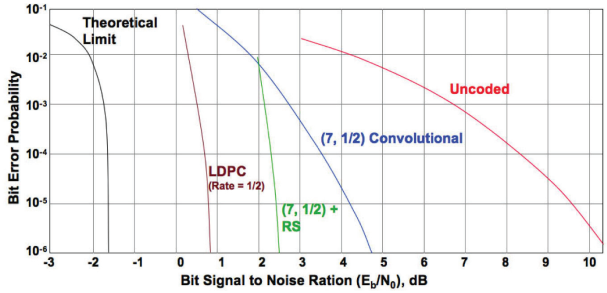

Figure 7. *Comparison of Various Coding Schemes*

NASA's SCaN office, which has made an effort to avoid overlaps and leverage synergies. However, there are potential synergies with other NASA pro-grams in areas such as optical instruments and cryogenics that must be further investigated.

2.1.2. Radio Frequency Communications

Current Status:

Radio Frequency (RF) Communications is used on all of NASA's current space missions.

Near-Earth missions drive the current state-of-the-art for data rates, data volume, and bandwidth efficiency. With today's technology, downlink data rates can be more than 1 Gbps. The highest available NASA data rate, however, is 300 Mbps from TDRSS.

Since communication performance is inversely proportional to the distance squared, deep space missions tend to push the art in other directions – particularly in power efficiency. Mars Reconnaissance Orbiter (MRO), which can return 6 mbps when Mars and Earth are at their closest distance, is the state of the art in deep space communications.

Currently, there are critical phases of our missions where standard RF techniques do not work. These include communication through launch plumes and communications through plasma during Earth reentry. We need to mitigate these problems to ensure mission safety and success.

Major Challenges:

The major challenge is to keep in front of the mission communities need for more and more data return. In addition, we will need to make significant strides in increasing uplink and developing innovative approaches to conduct emergency communications to enable safe and efficient human exploration and autonomous robotic space operations. Since radio spectrum is controlled by international law, we are always challenged to get as much use out of our allocated spectral bands as possible. RF links between spacecraft (e.g., crosslinks or support of in-situ exploration) will become more prevalent in future mission concepts. We will also need to increase the performance of in-situ surface wireless communication on bodies other than Earth. Communications through harsh environments provides a major challenge during critical phases of our missions. Finally, we must manage these new technologies together with the in-crease in number of spacecraft and ever more complex mission operations without huge in-creases in operations or maintenance costs. Since this technology area is more mature than optical communications, developments should also focus on more efficient use of power, available spectrum, mass, and volume.

Overcoming the Challenges:

As depicted in the TASR, early RF communications development will focus on development of a reprogrammable software defined radio that can then be used as an infusion path for subsequent developments. The mid-term focus is on reducing SWAP for major components. The following paragraphs describe the technical solutions that will be executed to address the challenges.

Spectral-efficient technology: Spectral bandwidth is a precious and legally enforced commodity. We need to get as much use as we can from what we have been allocated. This means using ever more clever ways of fitting more bits into the same number of Hertz. It also means being ever-vigilant to reduce radio frequency interference and stay robust to interference from others. High order modulation schemes (e.g. 8PSK and

Table 3. *Mapping of RF communications tasks into the Top Technical Challenges*

	1 Remove Comm. as a Constraint	2 Remove Nav. as a Constraint	3 Minimize Impact of Latency	4 Minimize user burden	5 Integrity & Assurance	6 Lower Life-cycle Cost
Spectral-Efficient Technology	X			X		
Power-Efficient Technology	X			X		
Propagation	X	X			X	
Flight and Ground Transceivers	X	X		X		
Earth Launch and Reentry Communications	X				X	
Antennas	X			X		X

16 QAM) as well as careful pulse shaping (e.g., GMSK) are examples of current technology investments in this area.

Power-efficient technology: Spacecraft power is a precious commodity for many missions and the communication system is a traditional major user of this power. We must continually strive to reduce the amount of power required to return each bit from space. Efficient power amplifiers and error correcting codes are two of the standard technique for advancing power efficiency. Another is the use of higher carrier frequencies such as moving from X-band (~8 GHz) to Ka-band (~32GHz) in deep space. Further gains are possible through the use of advanced data compression, coding, and modulation techniques – and through careful combinations and creative integration of these with data sampling.

Propagation: The more we understand about how our signals move through space and atmospheres in the allocated frequency bands, the more innovative we can be in developing better-performing transmission and detection algorithms. This knowledge, including atmospheric modeling and simulation, is needed for development of future concepts for arraying both spacecraft and ground antennas, and critical for developing robust reentry communications.

Flight and Ground Transceivers: Develop the technology to enable the future radio systems (flight and ground) including miniaturized components, cognitive systems (self configuring and environmentally aware), weak signal operations, and lower operations and maintenance costs.

Earth launch and reentry communications: Characterize the harsh environment and develop solutions such as use of ultra wide band (UWB), space-borne terminals, adaptive, or cognitive systems.

Antennas: Both flight and ground antennas are considered in this element. As we move to higher carrier frequencies, we need to ensure we can develop antennas that are efficient and can be pointed. We also need to consider arrays of antennas as an option to building ever-larger single dishes. For flight systems, we need to investigate various forms of deployable structures, as well as techniques for adaptively combing apertures. Combining of antennas for receiving signals is already advanced. However, focused technology development should be directed towards antenna combining in the transmit direction.

Overlaps and Potential Synergies:

NASA currently invests in RF communication technology in two main areas. The NASA Space Communications and Navigation (SCaN) Office in SOMD maintains a technology program that provides the main Agency investment. In addition, mission directorates (most notably the Mars Program within SMD) typically invest in mission-specific systems. There are likely other synergies that must be investigated with NASA programs that invest in science instruments such as radars. NASA is also investigating synergies between RF and optical communications including the use of common system elements.

2.1.3. Internetworking

Current Status:

To date, most space communication scenarios have involved fundamental point-to-point links between a spacecraft and Earth. Today's specialized link-layer protocols and carefully planned and scheduled link operations have thus far been adequate to meet the needs of missions. Currently, there is a rudimentary internetworking capability between ISS and the ground using standard Internet protocols. There have also been a number of technology demonstrations of space-based internetworking technologies, including the CANDOS Project (Communications and Navigation Demonstration on Shuttle) that demonstrated mobile IP, the CLEO Project that placed a Cisco router in low Earth orbit, and Deep Impact Networking Experiment (DI-NET) that placed DTN protocols in deep space.

Major Challenges:

Availability: The terrestrial Internet assumes that there is always a real-time and reliable path between the source and destination. In space, our nodes are often not available for communications, either because the spacecraft is not in view or because it is busy doing other tasks. Messages must be able to pass through this network even when intermediate nodes appear and disappear.

Latency: Space links, because of the long distances involved, are not conducive to standard Internet solutions. In addition, the long latency makes many real-time adaptive techniques impossible.

Autonomous operations: As missions become more complex and further from Earth resources, there will be a need to support more autonomous operations with minimal Earth contact. With increasing levels of autonomy, entirely new classes of missions are also being envisioned where assets would routinely coordinate among themselves without ground intervention to achieve mission

Table 4. *Mapping of internetworking communications tasks into the Top Technical Challenges*

	1 Remove Comm. as a Constraint	2 Remove Nav. as a Constraint	3 Minimize Impact of Latency	4 Minimize user burden	5 Integrity & Assurance	6 Lower Life-cycle Cost
Delay-Tolerant Networking	x		x	x	x	x
Adaptive Network Topology	x		x	x	x	x
Security					x	
Integrated Network Management			x	x	x	x

objectives. There will be a need for remote communications networks to enable communication between platforms, as well as a need to configure and maintain dynamic routes, manage the intermediate nodes, and provide quality of service functionality.

Information Assurance: NASA information is vulnerable to many factors including hardware, software, and human intervention. As NASA's science and information sources become inter-leaved with terrestrial public domain networks to support initiatives such as STEM and interna-tional collaboration, it will be imperative to protect NASA's assets and operations, and facilitate seamless authentication of users and assuring that all messages are transferred without compromise.

Complex Network Topologies: Earth Science, Astrophysics, Human Origins, and Solar-Terrestrial missions will require multiple communications and networking topologies to meet future missions, to include multiple spacecraft flying in formation e.g. to create unprecedented telescope apertures and interferometers for imaging fainter, smaller, and more distance objects. Commercial in-space servicing and orbital debris removal, heavy lift vehicle stacking, and assembly of separately launched telescope mirrors require precise navigation and proximity communications. Complex and time-varying networks of spacecraft and sensors must be capable of sharing rich, near-real-time streams of information.

Minimizing Spacecraft Burden: Minimize the implementation footprint of the internetworking software, memory, and processing for spacecraft nodes is essential for space implementation.

Overcoming the Challenges:

As depicted in the TASR, the early focus will capitalize on investments made by NASA in DTN technology development that will enable future networking capabilities throughout the solar system. This is followed by expanding the functionality to include a broader spectrum of communication and navigation services exploiting autonomous and cognitive technologies. The technical solutions that will address the challenges are described below.

Disruption-Tolerant Networking (DTN): Internetworking protocols (e.g., surface wireless and proximity, quality of service, network management and information assurance, adhoc networking, etc.) are critical to enable automation of connections and data flows and disconnection (store-and-forward) multi-hop friendly applications. In fact, the Agency has recently invested in DTN to provide a set of basic services in the FY2015 timeframe to allow coordination among platforms. Advances in space-based, high speed routing technologies will also be necessary to enable internetworking across future high bandwidth links (proximity and end to end).

Adaptive Network Topology: Develop robust ad hoc and mesh networking of mobile elements to coordinate timing, position, and spacing within the operational needs of human and robotic missions. Consider advanced methods of channel access including multiple and demand access. Maintain quality of service across the dynamic network. Traffic modeling and simulation will be critical tools to define and validate topologies.

Information Assurance: Develop information assurance architecture technologies to a) ensure system safety, data integrity, availability and, when required, confidentiality and b) to enable use of all available links and networks – some which may be provided by other agencies or countries. Space information assurance protocols will also enable system self-awareness of actual versus expected patterns of operation to detect anomalies that may indicate information assurance breaches, system failures, or safety hazards and have the ability to automatically execute plans to reroute critical traffic in the event that critical systems are compromised or destroyed.

Integrated Network Management: Develop integrated network management architectures and protocols to effectively support autonomous operations with adaptive network monitoring, con-figuration and control mechanisms including integrated health management (IHM).

Overlaps and Potential Synergies:

As the need for autonomous operations and reduced reliance on Earth based resources evolves, internetworking protocols and technologies will be needed to support challenging missions within SMD and ESMD and for complex topologies supporting future aviation applications in ARMD/FAA (e.g. high density terminal operations). Additionally, NASA will seek to leverage advances in commercial and other government agency's communications and networking technology development, to include network mobility, ad hoc networking, and security.

2.1.4. Position, Navigation, and Timing

Current Status:

NASA's current PNT state-of-the-art relies on both ground-based and space-based radiometric tracking, laser ranging, and optical navigation techniques (e.g. star trackers, target imaging). A variety of radiometric ranging techniques are used throughout the NASA communications networks. Post-processed GPS position determination performance is at the cm-level at Near-Earth distances and meter-level at High Earth Orbit distances. Autonomous real-time GPS performance, such as that produced by the Goddard Enhanced Onboard Navigation System (GEONS) can achieve accuracies of at least 20 meters.

Position determination performance is better than 10m at near-Earth distances, and is 10s of km at the distance of Mars. The Deep Space Network (DSN) employs a high-accuracy Very Long Base Line (VLBI) method that yields position determination performance of 1km at Mars, a few kilometers at Jupiter, and 100s of km at distances beyond Jupiter. Optical navigation methods yield position determination performance of 1 km at near-Earth distance and 10s of km at Mars distance.

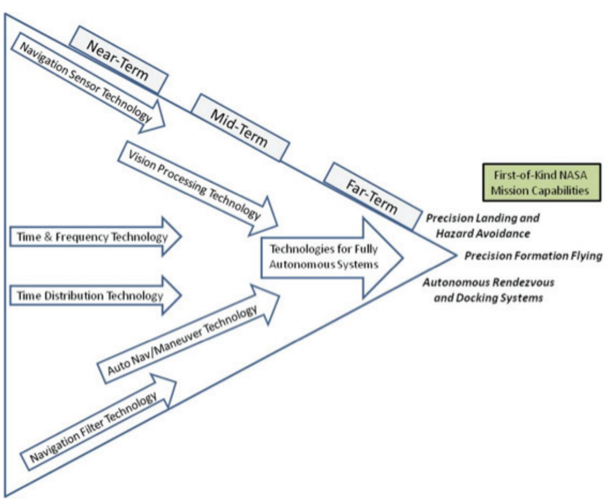

Figure 8. *PNT Development Timeline*

Navigation relies on precision time and frequency distribution and synchronization. The near-Earth GPS-based time/frequency reference and time transfer capabilities are in the nanosecond range and the micro-second range, respectively. The use of quartz resonators for on-board time/frequency generation is most common. The GPS satellites employ rubidium and/or cesium atomic clocks for ultra-stable timekeeping. The short-term and medium-term stability performance of the current generation of space clocks, in terms of Allan Variance, currently spans the 10^{-13} to 10^{-14} range for intervals of 1^{-10} seconds and is within the 10^{-13} to 10^{-15} range for longer intervals of 100 seconds. Current long-term space clock performance ranges from 10^{-12} to 10^{-13} over time intervals greater than 1000 seconds.

All the above PNT methods are technically and operationally mature and have thus far been adequate for NASA's mission needs.

Major Challenges:

Future missions will require precision landing, rendezvous, formation flying, cooperative robotics, proximity operations (e.g., servicing), and coordinated platform operations. This drives the need for increased precision in absolute and relative navigation solutions.

As we operate further from Earth and perform more complex navigational maneuvers, it will be necessary to reduce our reliance on Earth-based systems for real-time decisions. This will require reduced dependence on ground-based tracking, ranging, and trajectory/orbit determination support functions (to minimize latency and availability constraints). Since timing is a fundamental parameter for adequate navigation, we will need increased precision in reference time/frequency generation, time/frequency distribution, and synchronization. Space-qualified clocks are not available today with the desired precision for future missions. Reducing reliance on Earth systems also requires clocks that are orders of magnitude more precise that the best space-qualified clocks today. Also, the use of multi-hop communications presents a challenge for PNT support in terms of measurement of radiometric tracking data (RMTD). The transit delays through each node and the ephemeris knowledge of each node contribute to RMTD measurement errors, hence PNT errors on the final node. Increased precision in each individual node's PNT system will be required in order to minimize the error contributions of each hop to the final node's PNT solutions.

The platforms which are "first down" on a NEO or a planetary surface may have limited ground inputs and no surface/orbiting navigational aids. NASA currently does not have the navigational and trajectory/attitude flight control technologies that permit the fully autonomous capabilities for approach and landing.

Overcoming the Challenges:

As depicted in the TASR, the early focus is on increasing PNT accuracy and precision, with the later focus on autonomy. An overall goal of these technology investments is to position NASA to conduct human space flight missions beyond LEO. The following paragraphs describe the technical solutions that will be executed to address the challenges.

As notionally depicted in figure 8 above, we envision a phased PNT technology development effort over the next 15-20 years that starts with foundational work in timekeeping and time/frequency distribution/time synchronization coupled with developments in navigational sensors and filters. Research into the next generation of multi-purpose navigation filtering techniques is needed (e.g. adaptive filtering) to improve on the current ad-hoc mission-unique Kalman Filter based approaches used since Apollo. The development of component-level PNT technology building blocks will permit the synthesis and implementation of early semi-autonomous (e.g. supervised autonomy) PNT flight systems. Subsequently, based upon the flight results of the semi-autonomous missions together with investments in autonomous systems technology, NASA will be in an excellent position to fly missions having fully autonomous PNT functions. Attaining this goal will have benefits for human and robotic spaceflight in all flight regimes: near-LEO, beyond-LEO, and deep space. There will be interaction between the technology areas identified in figure 8 as NASA works towards the goal of having fully autonomous PNT functions available where needed. The convergence of the technology areas indicated in the figure will culminate in first-of-a-kind NASA capabilities for AR&D and PFF missions, which absolutely require the highest level of autonomy and PNT performance.

Timekeeping: The development of a new integrated space-qualified timekeeping system with ultra high accuracy and frequency stability performance is to be considered not only for PNT functions but also for fundamental physics, time and frequency metrology, geodesy and gravimetry, and ultra-high resolution, VLBI science applications. The advanced timekeeping systems sought could be based upon highly stable quartz crystal resonators or on techniques which measure atomic transitions to establish the frequency standard for the timing system—including optical clocks. Major technical challenges for space clocks using quartz resonators include reducing their sensitivity to the on-board thermal environment conditions and their susceptibility to magnetic and electric field, g-force, and ionizing radiation effects. The primary technical challenges for atomic-based space clocks are to reduce their complexity and cost while maintaining their high-end performance. Common technical challenges include reducing the overall timekeeping system SWAP resource requirements, radiation hardened low- noise clock readout electronics, and lastly the software algorithms which process the clock measurements and estimate/propagate the timekeeping model which generates the time/frequency signal output(s). Advanced time-keeping systems will require technology developments to address the aforementioned technical challenges. Research is also needed into new timekeeping system architectures in which outputs of an ensemble of clocks are weighed and software filtered to synthesize an optimized time estimate.

Time/Frequency Distribution: NASA mission applications, both for navigational functions and in the fundamental science realm, will benefit from having a robust and reliable common time/frequency reference that can be shared precisely across the Solar System. The ability to perform precise time/frequency transfer is coupled with the anticipated technology developments for space clocks. As the frequency stability of space clocks improves the need for precise time/frequency transfer will increasingly emerge as the driving 'timing' problem. Technology investments are needed to provide the service function of collecting, formatting to a common interface standard, and communicating PNT data across a heterogeneous network of space and ground based platform nodes. Research and development is required at three levels: systems re-search (e.g., time/frequency distribution architectures/techniques/methodologies, system error/uncertainty modeling), hardware component development (e.g., RF or optical communications devices to affect time/frequency transfers), and software component developments (e.g., filtering algorithms to propagate real-time estimates of the common time/frequency reference). Nanosecond-level time transfer capability across the Solar System is envisioned as a long-term goal given that this level of time/frequency transfer is the state of the art on Earth. We will also need to develop methods for accurate time/frequency distribution in the space Internetworking environment—especially when there is not a direct real-time path back to Earth.

On-Board Autonomous Navigation and Maneuvering Systems: The principle mission drivers for autonomy are: servicing/assembly, sample return, formation flying, and pinpoint landing. In-vestments in technologies to implement autonomous on-board navigation (and maneuvering) will permit a reduction in dependence on ground-based tracking, ranging, trajectory/orbit/attitude de-termination and maneuver planning support functions. Autonomous navigation and maneuvering technologies will be needed for all classes of space platforms: from robotic spacecraft and planetary landers to crewed exploration vehicles to planetary surface rovers. In the near-term gradually increasing levels of autonomous navigation capabilities will allow platforms to go longer between time and state vector updates from the Earth. A significant benefit to be attained in this case will be a reduction in the burden of routine navigational support. Less reliance on the ground-based navigational support will reduce communication requirements on network services making them available for missions with less on-board autonomy. An additional benefit that will accrue from having autonomous on-board navigation and maneuvering capabilities will be an increase in platform's operational agility, enabling near real-time re-planning and opportunistic science. In the longer term fully autonomous navigational capabilities will enable classes of missions which would otherwise not be possible due to round-trip light time. Investment in the following specific technologies will be needed: autonomous navigation system architectures and techniques, autonomous navigational planning and optimization algorithms to include highly-reliable approaches for fault management, sensors for on-board autonomous navigation, navigation filter algorithms, on-board maneuver planning and sequencing algorithms, fault-tolerant attitude control systems for autonomously orienting the platform, efficient autonomous navigation system verification and validation methodologies and ground-based Hardware-in-the-Loop systems testbed, and in-space demonstration testbeds.

Next Generation Sensors/Vision Processing Systems: Specific technologies to be developed include optical navigational sensor hardware (such as high resolution flash LIDAR sensors, visible and infrared cameras), radar sensors, radiometrics, fine guidance sensors, laser rangefinders, high volume/high speed FPGA-based electronics for LIDAR and other imaging sensor data processing, sensor measurement processing algorithms, synthetic vision hardware/software, and situational awareness displays.

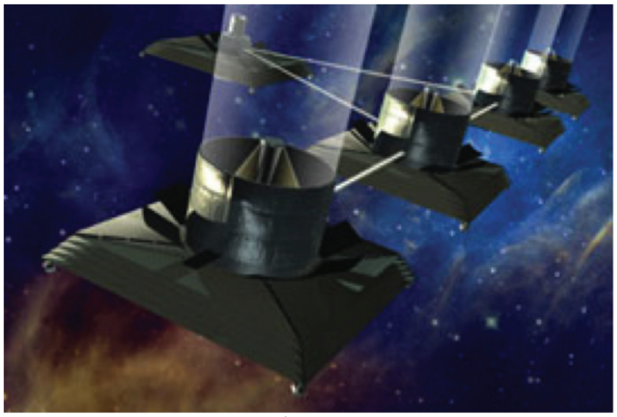

Figure 9. *Formation Flying Mission Concept*

Relative and Proximity Navigation: The capability to perform multi-platform relative navigation (i.e., determine relative position, relative velocity and relative attitude/pose) directly supports cooperative and collaborative space platform operations. There is a cross-cutting mission 'pull', from both the envisioned human exploration missions as well as the robotic science missions, for relative navigation technologies. One well-recognized such cooperative operation that relative navigation enables is Automated Rendezvous and Docking (AR&D) of two or more space plat-forms. The collaborative operations of satellite formations or coordinated surface rovers operations with orbiting spacecraft are other mission applications enabled by relative navigation. The specific component level technologies to be developed here include, but may not be limited to, the following: high resolution/high frame rate visible and infrared imaging sensors, high speed sensor data processing electronics, precision narrow-beam laser rangefinder sensors, navigation filters (e.g., adaptive filters) and associated algorithms to sort and selectively weight data from multiple relative sensor input sources, mid-to-short range RF or optical intra-spacecraft communications systems for transmission of relative navigation state information and other data between the cooperating spacecraft.

Autonomous Precision Formation Flying PNT: This system capability builds upon and coalesces several of the PNT technologies previously described in this Section. The supporting technol-

Table 5. *Mapping of PNT tasks into the Top Technical Challenges*

	1 Remove Comm. as a Constraint	2 Remove Nav. as a Constraint	3 Minimize Impact of Latency	4 Minimize user burden	5 Integrity & Assurance	6 Lower Life-cycle Cost
Time Keeping		X				
Time Distribution		X	X	X		
Onboard Autonomous Navigation and Maneuvering Systems		X	X			
Next Generation						
Sensors/ Vision Processing Systems		X		X		
Relative and Proximity Navigation		X	X			
Autonomous Precision Formation Flying PNT		X	X			X
Autonomous Approach and Landing		X	X			

ogies include differential (relative) navigation, sensors/vision processing systems, space clocks and time/frequency distribution systems, on-board system navigation and autonomous or-bit/attitude maneuvering. In this technology "push" case much higher level of PNT performance is needed to satisfy the stringent Precision Formation Flying (PFF) requirements imposed by en-visioned distributed observatories such as planet-finding interferometers. Advances in PNT technologies are necessary but not sufficient to enable an autonomous PFF capability for NASA. The PNT technologies sought are for autonomous planning and optimization algorithms, higher performance relative navigation sensors, lower noise, higher speed sensor processing electronics and enhanced relative navigation filters. These technology developments should be phased to attain TRL 6 by 2022. An opportunity for in-space validation of an integrated PFF PNT system will then need to be identified prior to the PFF IOC date we set of 2025.

Autonomous Approach and Landing: An integrated ensemble of active and passive optical and RF sensor hardware with supporting real-time vision processing algorithms will be a fundamental part of any autonomous Guidance, Navigation, and Control (GN&C) system intended to perform safe and controlled precision landings on or contacts with the surface of any solid body in the Solar System. Precision terrain-relative navigation while simultaneously detecting and avoiding surface hazards is a multidisciplinary technology challenge focused on improving real-time situational awareness and platform responsively in uncertain operational environments. Technologies that allow an increased reliance on in-situ observations, data fusion, and autonomous PNT will be sought. Significant investments in technologies for vehicle on-board sensing, perception, reasoning, planning and decision making will be needed well beyond what current technology programs have accomplished. This is a system-level capability built strongly, but not solely, upon the several of the PNT technologies cited above that enable Autonomous Maneuvering, Sensors/Vision Processing Systems, and On-Board Navigation. Sensors and algorithms for path planning and optimization, constraint handling, integrated system health management, fault management (e.g., FDIR), event sequencing, optimal resource allocations, collaborative sensor fusion, sensor image motion compensation and processing, pattern recognition/pattern matching, hazard search and detection strategies, feature (e.g., hazards) location and mapping, high performance inertial sensors and celestial sensors, accurate and fast converging vehicle state estimation filters and for adaptive flight control systems that provide precise and agile maneuvering.

One other particular technology area that has synergy between the navigation on and around NEO/Planetary bodies as well as conducting scientific surveys is the development of a new generation of high performance gravimetric/gravity gradiometer sensors using emerging cold atom sensor technology. System architectures and supporting technologies for navigational beacons that aid spacecraft approach and landing are needed. The navigational beacons can be deployed on early exploration satellites. Navigational beacons can be integrated into the precursor satellites which will be used to map and study planet and NEO surface characteristics. These orbiting beacons can be part of a navigation constellation for improved vehicle positioning during the approach and landing mission phase. Likewise, body-based beacon landing systems derived from GPS pseudolite technologies can be used for accurate landing systems. A pre-landing mission can deploy three to five beacons. These beacons can land in rough, unknown locations using air-bags or parachutes. Through repeated observation, these beacons' positions can

Table 6. *Mapping of integrated technology tasks into the Top Technical Challenges*

	1 Remove Comm. as a Constraint	2 Remove Nav. as a Constraint	3 Minimize Impact of Latency	4 Minimize user burden	5 Integrity & Assurance	6 Lower Lifecycle Cost
Radio Systems	X					
Ultra Wideband	X			X		
Cognitive Networks			X	X	X	X
Science from the Comm Systems				X		X
Hybrid Optical Comm & Nav Sensors	X	X		X		
RF/Optical Hy-brid Technology	X	X		X		X

be precisely determined. With knowledge of beacon location, future landing craft can use precise timing beacons for improved navigation accuracy similar to GPS pseudolites.

Overlaps and Potential Synergies: There are several synergetic PNT technology developments underway at NASA. ESMD and SMD have similar navigation interests. Both are pursuing autonomous precise landing capability that would support their respective missions.

2.1.5. Integrated Technologies

Current Status:

Current NASA flight transceivers are capable of performing communication and radiometrics. However, they are not aware of their environment and do not react to it. There are only limited network level capabilities. Ground systems have just begun integrating network functionality. Currently, NASA missions can take advantage of the RF communication link as a science instrument — gleaning information about intervening atmospheres, gravity fields and surface terrains. Lidars have demonstrated the potential for similar capability on optical links. Today, RF and optical systems are developed and operated separately, even though there are components that could be shared. Modeling and simulation is used today for research and development of communication and navigation systems. Finally, the location and status of our Astronauts and their implements is determined through manual means on the ground.

Major Challenges:

Challenges include reducing the user burden and ground infrastructure through integration of technologies, reducing costs through innovative systems-level analysis, exploiting optical communication links as science instruments while increasing performance over the RF equivalent and increasing the flexibility of communication and navigation systems.

Overcoming the Challenges:

As depicted in the TASR, this area integrates technologies developed in the other areas with the goal of reducing SWAP and enabling multi-purpose systems while at the same time enhancing mission autonomy.

Radio Systems Technology: Exploit technology advances in RF communications, PNT, and space internetworking to develop advanced, integrated space and ground systems that increase performance and efficiency while reducing cost. For example, a multipurpose software defined radio might be developed that can changes its function with mission phase and requirements.

Ultra-Wideband Technology: Develop radio technology for short-range, high-bandwidth communications and navigation. For example, a surface explorer may carry an ultra-wideband transceiver/subsystem which enables it to (in a single burst) communicate with another rover or orbiter in proximity, determine a precise range to the other element (positioning), and listen for returns from the same burst to produce a navigation map for the terrain in proximity to the rover (navigation). This would not only reduce the mass of the rover consolidating three functions into a single system, but may also reduce power by using a single burst to perform all three functions.

Cognitive Networks: Develop a system in which each node is dynamically aware of the state and configuration of the other nodes. Today, most of the decisions in space communications and navigation today are made on the ground. Communications and navigation subsystems on future missions should interpret information about their situation on their own, understand their options, and select the best means to communicate or navigate. For example, a node in such a network might be aware of the positions and trajectories of all other nodes, inferring this entirely through network communications and modeling.

Science from the Communications System: Enhance the use of RF communications systems to perform science measurements. Develop the capability to use optical communication links to make science measurements. Consider using in combination to improve accuracy. Expand the spectral width of the signals to enable more information about sub-surfaces. In addition, promising new research indicates that with further technology development it may be possible to deter-mine the Earth's wobble using the same technology being developed for the arraying of TDRSS satellites. This would provide a continuous real-time measurement of the wobble as a by-product of tracking TDRSS with this new technology.

Hybrid Optical Communication and Navigation Systems: These are sensor systems that are dual use in nature providing a synergistic benefit to both communication and navigation functions. Innovative approaches could include exploiting an optical communications terminal to perform navigational measurements such as star sighting, or a star tracker technology developed to communicate at very high data rates. Such advances will decrease the SWAP burden to users.

RF/Optical Hybrid Technology: Optimize the architecture and integrated components into a system that can be used to support hybridized RF and optical communications in the same asset, in diverse atmospheric (weather) and in-space conditions. This includes both the electronics and the complex integration of collinear antenna and weather elements within the system. Potential benefits include SWAP savings and provision of an RF beacon for acquisition and pointing.

Overlaps and Potential Synergies:

By its very nature, we expect many sources will exist within NASA for the elemental technologies that will be integrated in this area.

2.1.6. Revolutionary Concepts

Current Status:

Most prior NASA investments in communications and navigation have been in evolutionary improvements and in technologies that are based on electromagnetic principles. Additionally all these systems have a heavy dependence on Earth based services and references. The Agency will continue to invest in pushing the advancement of traditional communications and navigation technologies to meet future mission needs. However, this roadmap also provides a framework to identify revolutionary concepts for potential development. None of these technologies are "pulled" by any future mission. These are inherently risky investments with a high probability of failing to achieve their goal—but a very high payoff if they are successful. Technologies that show promise will be transitioned to the appropriate communications and navigation sub-element for appropriate infusion into missions or enabling infrastructure.

Major Challenges:

The critical thrust for this technology sub-element is to develop new ways of approaching the key communications and navigation challenges that radically improves the performance. Changes should typically be several orders of magnitude in increased performance or decreased user burden to be considered.

Overcoming the Challenges:

As depicted in the TASR, this area provides innovations and game-changing solutions that will provide mission planners and scientists freedom to develop and implement more complex missions and enable new science and exploration goals. Several revolutionary concepts that could enable new classes of missions have been identified are presented as examples of possible tasks.

X-Ray Navigation: The XNAV concept uses a collection of pulsars—stellar "lighthouses"—as a time and navigation standard just like the atomic clocks of the GPS. Unlike GPS satellites, XNAV pulsars are distributed across the Galaxy, providing an infrastructure of precise timing beacons that can support navigation throughout the Solar system. Since their discovery in 1967, pulsars have been envisioned as a tool for deep space navigation. An XNAV system measures the arrival times of pulses from pulsars through the detection of individual X-ray photons.

X-ray Communications: Space-based communications can benefit dramatically from technological mastery of the x-ray portion of the spec-

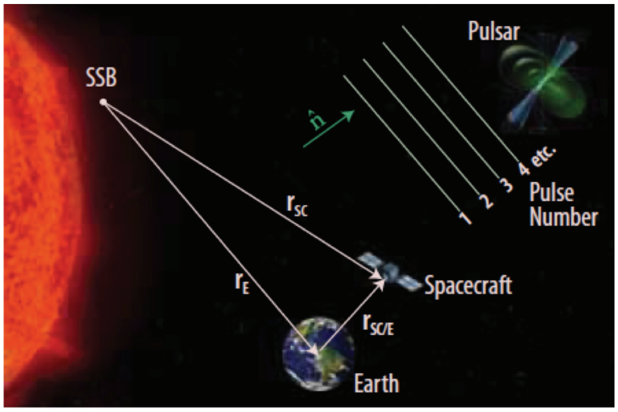

Figure 10. *Notional Xnav Architecture*

trum. Fundamentally, two major advantages of x-rays (relative to optical, microwave, or radio-frequency technologies) should be exploited. First, the short wavelength offers very low divergences, which has the potential to lower requirements on SWAP relative to longer-wavelength technologies, and to provide secure inter-satellite communications. Second, the exceedingly high carrier frequency means significantly larger band-widths for information transmission if technologies for modulating x-rays are further developed.

Neutrino-based Navigation and Tracking: Neutrinos are small near light speed particles with no electric charge. Neutrinos can be generated through nuclear reactors or particle accelerators. Detection of neutrinos however, currently requires massive detectors made of thousands of tons of liquid buried in the ground. Since Neutrinos can travel through most matter, they could be used for long-distance signaling when line-of-sight cannot be guaranteed. A possible ranging method using neutrinos is to modulate the neutrino output from a nuclear reactor or particle accelerator on a spacecraft and detect this output on an Earth base station. The modulation would encode timing information from an atomic clock synchronized to Earth, which can be used to calculate range. NASA, and North Carolina State University have demonstrated the use of neutrinos for communications.

QKD/Quantum Key Distribution: Encryption schemes entail distribution of a secret key among legitimate users and as such are susceptible to interception by an unwanted eavesdropper. While traditional encryption schemes and codes can be compromised and/or intercepted, QKD promises absolute secure transmission of the key codes that are essential to encrypt messages with tamper proof information assurance. A quantum communications channel is inherently se-cure since the mere act of observing the communications channel will be apparent to both par-ties. While it is acknowledged that other government agencies have the technical lead in the investigation of this concept, it would be of value for NASA to be cognizant of the advances of QKD and quantum entanglement as a potential stepping stone for quantum communications.

Quantum Communications: This is the art of transferring quantum states (which encode information) between two points. It should be noted that there is significant debate in the scientific community as to whether this technology will enable faster than light communications. While quantum entanglement has been demonstrated at a few tens of kilometers, long-range communications face critical challenges. High flux single photon sources as well as entangled photon sources need significant development in order to enable long-range communications. NASA should at minimum stay abreast with the research in this area to determine if the purported ad-vantages make sense for space applications (e.g. no antenna needed, no broadcast power, very secure with high data rates, not line of sight, etc).

Superconducting Quantum Interference Filter Microwave Amplifier: This revolutionary concept represents a significant paradigm shift by using magnetic field detection instead of electric field detection and capitalizes on techniques demonstrated in the sensors community. From a fundamental physics point of view, the magnetic field detection process holds promise for a significant advantage in sensitivity. This concept incorporates a Superconducting Quantum Interference Device array for detecting extremely weak magnetic fields to enable a new type of signal detection process. Though fundamental principles have already been demonstrated, it is not known how much of the theoretical sensitivity improvement can be realized. Integration of a "flux concentrator" at frequencies of interest to NASA and a practical Superconducting Quantum Interference Filter has not been demonstrated. Issues such as flux motion within the superconducting film, which reduces sensitivity, and system benefits with the refrigeration system included need to be assessed.

Reconfigurable Large Apertures:

The vision is to form large space apertures using constellations of nanosat systems. This will require advances in nanotechnologies, semiconductor processors, computing architectures, advanced materials power and propulsion, miniaturized communications components, adhoc/wireless network protocols, and cognitive swarm operations.

3. INTERDEPENDENCY WITH OTHER TECHNOLOGY AREAS

The Table below exhibits the identified area of synergy or overlap with the other Technology Areas. Areas 4, 8, 11, and 13 are where Team 5 believes there may be the most overlap.

4. POSSIBLE BENEFITS TO OTHER NATIONAL NEEDS

Many technology advances in space communi-

Technology Area	Synergy or Overlap
2 In-Space Propulsion	Autonomous GNC maneuvers; Solar Sail Propulsion
3 Space Power and Energy Storage	Power beaming; Power antennas
4 Robotics and Telerobotics	Navigation sensors; Autonomous GNC; Internetworking; Navigation for flying and submersible robots; Near real-time communications with the public; Human/Robotic interaction
6 Human Health, Life Support and Habitation Systems	Very high bandwidth communication for telemedicine; RFID asset tracking; Software uploads
7 Human Exploration Destination Systems	Very high bandwidth communication for telemedicine; RFID asset tracking; Software uploads
8 Science Instrument, Observatories, and Sensor Systems	Detectors; Telescopes/Antennas; Enabling communications; Science using the communication system; Onboard wireless avionics; Multi-purpose (science, comm. and nav) sensors and systems
9 Entry, Descent, and Landing Systems	Reentry Communications; Precision landing
10 Nano Technology	Nano transceivers
11 Modeling, Simulation, and Information Processing	Atmospheric models; High performance computing platform; Networking; Data compression
12 Materials, Structure and Mechanical Systems, and Manufacturing	Large apertures; Lightweight materials
13 Ground and Launch System Processing	Telemetry systems using new spectrum; Secure access; On-demand frequency allocation (cognitive radios); Adaptive data compression; Intelligent network topologies (DTN); Interspacecraft communications; Universal communications beacon for hailing; Range safety; Space-based range; Comm through plume

cations technology are transferable to the commercial communication environments. For example, spectrum efficient technology is a prime concern of the telecommunications industry and those US Government agencies that manage spectrum. Similarly, advanced networking that can autonomously deal with communications disruptions has potential terrestrial commercial applications as part of the internet. In general, communication technology developed for space applications can be implemented in the commercial sec-tor, even though the actual spectrum frequencies may differ. This applies to both the commercial terrestrial and space communication sectors. In addition, many commercially developed communication technologies can be implemented in NASA systems and can be used directly or modified for space use.

Because of the commonality of many of the components and methods, NASA's communication technology has always been synergistic with the radio astronomy community, including the National Radio Astronomy Observatory, and the National Science Foundation (the major US sponsor of the Square Kilometer Array). Many other non-profit and academic organizations can bene-fit from space communication technology development through challenging opportunities for researchers to contribute to the development efforts directly or through educational outreach programs.

Sharing the NASA adventure with all American citizens is a top goal for NASA. Space communications technology development can enable in the future the average citizen to view from his living room, in live, full motion, three dimensional video, the exploration activities of our robots and astronauts on their missions of discovery.

NASA space communications technology has traditionally been of interest to other US Government agencies. This is evidenced by the fact that many past space communication technology developments have been joint projects with other agencies. There is reason to believe that this trend will continue. For example, in the recent "Report on Technology Horizons – A Vision for Air Force

Science & Technology" Are many technology areas of interest that are common with the areas cited in this roadmap such as: laser communications, secure RF links, dynamic spectrum access, quantum key distribution, as well as many others. Also, cybersecurity is an area of critical importance to all agencies, has been identified by the President as an area of R&D to be pursued by all US Government agencies and will be a driving requirement as we extend the terrestrial Internet into space. Therefore, as the roadmap in this document is executed there will be continuous dialogue with other US Government agencies to seek out areas of mutual interest and collaborative opportunities.

ACRONYMS

ALHAT	Autonomous Landing and Hazard Avoidance Technology
ATP	Authority to proceed
AO	Announcement of Opportunity
AU	Astronomical Unit
Delta-DOR	Delta Differential One-Way Ranging
DESDynI	Deformation, Ecosystem Structure and Dynamics of Ice
DINET	Deep Impact Networking Experiment
DOT	Deep Space Optical Terminal
DSN	Deep Space Network
DTN	Disruption (or Delay) Tolerant Networking
ECLS	Environmental Control and Life Support
EHS	Environmental Health System
ESMD	Exploration Systems Mission Directorate
GEONS	GPS-Enhanced Onboard Navigation System
GHz	Giga Hertz
GMSK	Gaussian Minimum Shift Keying
GN&C	Guidance Navigation and Control
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
GRAIL	Gravity Recovery and Interior Laboratory
GRO	Gamma-Ray Observatory
IOC	Initial Operational Capability
IP	Internet Protocol
ISS	International Space Station
JPL	Jet Propulsion Laboratory
LADEE	Lunar Atmosphere and Dust Environment Explorer
LEO	Low Earth Orbit
LIDAR	Light Detection And Ranging
LLCD	Lunar Laser Communications Demonstration
LST	Life Support Technologies
MMS	Magnetospheric MultiScale
MRO	Mars Reconnaissance Orbiter
MVP	Mass, Volume, Power
NEN	Near Earth Network
NEO	Near Earth Object
PAT	Pointing, Acquisition, and Tracking
PFF	Precise Formation Flying
PNT	Position, Navigation, and Time
POD	Precision Orbit Determination
PSK	Phase Shift Keying
QAM	Quadrature Amplitude Modulation
SCaN	Space Communications and Navigation
SMD	Science Mission Directorate
SoA	State of the Art
SOMD	Space Operations Mission Directorate
SWAP	Size, Weight and Power
TABS	Technology Area Breakdown Structure
TASR	Technology Area Strategic Roadmap
TDRSS	Tracking and Data Relay Satellite System
UWB	Ultra Wide Band
VLBI	Very Long Baseline Interferometry
XNAV	X-ray Navigation

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